

FIG. 4. cw histories for five  $\text{In}_{0.45}\text{Ga}_{0.55}\text{As}$  lasers operating at a constant power of 70 mW and with  $\lambda = 1102$  nm. 600- $\mu\text{m}$ -long, junction-up uncoated devices were operated at a heatsink temperature of 30 °C.

eliminated for devices placed into service, costly burn-in tests become unnecessary and because yield can be vastly improved.

The gradual degradation-limited lifetimes of these strained-layer lasers are also noteworthy. While GaAs quantum well lasers can perform as well as strained lasers, this is not typical<sup>14</sup>—median lifetimes between 1000 and 6000 h are quite common. Assuming that the present InGaAs laser devices are typical, a second advantage over GaAs accrues to this materials technology.

In summary, strained-layer InGaAs semiconductor structures have been fabricated into low-threshold lasers operating at 1100 nm. Although the quantum efficiencies are

lower than for GaAs quantum well lasers, these step-graded InGaAs devices may offer superior reliability by both the gradual and sudden degradation criteria.

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## Properties of $\text{WN}_x$ films and $\text{WN}_x/\text{GaAs}$ Schottky diodes prepared by ion beam assisted deposition technique

J. S. Lee, C. S. Park, J. W. Yang, J. Y. Kang, and D. S. Ma

Compound Semiconductor Department, Electronics and Telecommunications Research Institute, P. O. Box 8, Daeduk Science Town, Daejeon, Korea

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Low energy ion beam assisted deposition (IBAD) of refractory tungsten nitride films onto GaAs is attempted for the first time. This ion beam technique provides lower process pressure, and less ion damage to substrates and films than conventional reactive sputter deposition. Schottky diode characteristics of W/ and  $\text{WN}_x/\text{GaAs}$  and their thermal stability were investigated by capping the refractory films with  $\text{SiO}_2$  films and subsequent annealing at 700–900 °C for 30 min. While both tungsten and tungsten nitride contacts were stable up to 850 °C, the tungsten nitride contact showed better thermal stability and higher Schottky barrier height. The Schottky barrier heights of W/ and  $\text{WN}_{0.27}/\text{GaAs}$  diodes annealed at 850 °C were 0.71 and 0.84 eV, respectively. These preliminary results are comparable to those of the best results reported with the conventional sputtering methods.

Refractory metals and their low resistivity compounds play a significant role as gate materials in the self-aligned GaAs metal-semiconductor field effect transistor (MESFET) technology.<sup>1</sup> The self-aligned gate, acting as a mask during a source/drain implantation step, should be stable

without any degradation through the subsequent high-temperature annealing stage. High Schottky barrier height and good thermal stability are also required for the integrated device application. Studies on reactively sputter-deposited tungsten nitride contacts to  $n$ -GaAs have been reported

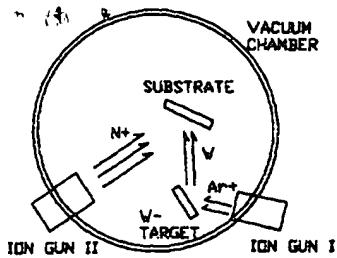


FIG. 1. Schematic illustration of ion beam assisted deposition of  $WN_x$  films.

within the last few years.<sup>2-7</sup> However, their Schottky properties revealed wide variations. The maximum attainable Schottky barrier heights reported are in the range of 0.5–0.95 eV, and the maximum temperature at which no degradation of the Schottky properties arises after annealing lies in the range of 700–850 °C.

In this study we made a first attempt to grow the tungsten nitride films on GaAs using an ion beam assisted deposition (IBAD) technique as an alternative deposition method. In contrast to the conventional reactive sputtering this technique provides the following advantages: lower process pressure, less ion irradiation-induced damage and heating, and better controllability of film composition. To explore the applicability of this technique into the GaAs integrated device fabrication, the Schottky properties and their thermal stability of W and  $WN_x$ /GaAs diodes were investigated. Our experiments and results were compared with the data of previous works performed using reactive sputtering.

*n*-type GaAs wafers with doping concentration of  $2 \times 10^{17} \text{ cm}^{-2}$  and (100) orientation were used as the substrate. The substrates were cleaned sequentially in trichloroethylene, acetone, and methanol for 10 min each. Film deposition was performed within a Commonwealth ion milling machine using Kaufman type gas source ion guns. Prior to deposition, the system was pumped down to  $5 \times 10^{-7}$  Torr and kept at 0.2 mTorr during film deposition by flowing Ar through a sputtering gun and  $N_2$  through a low-energy ion gun. As illustrated in Fig. 1, a focused Ar-ion beam from the 3-cm diam ion gun I was bombarded to a tungsten

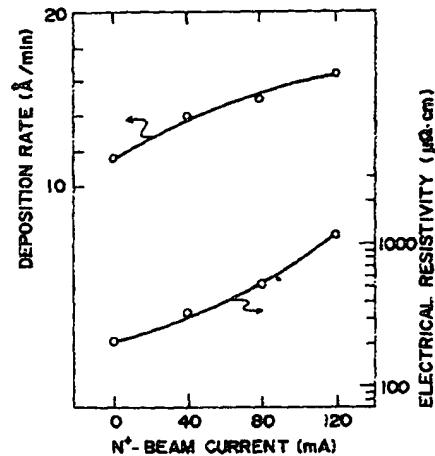


FIG. 2. The deposition rate and the electrical resistivity of  $WN_x$  films as a function of nitrogen-ion beam current.

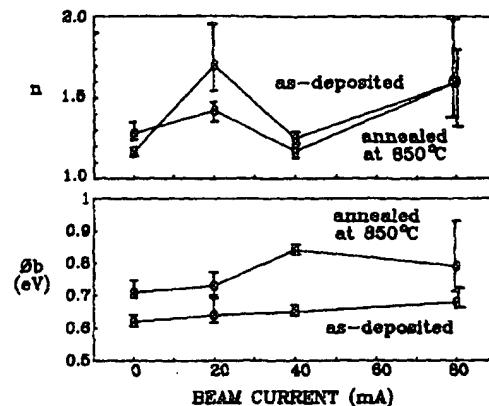


FIG. 3. The diode ideality factor  $n$  and the Schottky barrier height  $\phi_b$  of  $WN_x$ /GaAs diodes with the nitrogen beam current during  $WN_x$  deposition. The results are given with average values (filled circle) and scattering range (bars) of the data obtained from five samples or more.

target of 99.9% purity. At the same time, low-energy nitrogen ions were directly irradiated onto the substrate through the 12-cm-diam ion gun II. The beam voltage and current of the sputtering gun I were 1000 V and 20 mA throughout this experiment. But the beam current of the nitrogen-ion gun II was varied from 0–120 mA with a beam voltage of 70 V to control the nitrogen-ion dose. The thickness of the deposited film was measured with a stylus system and the sheet resistance with a four-point probe. The deposited films were also characterized with x-ray photoelectron spectroscopy (XPS) and x-ray diffraction (XRD).

Figure 2 shows the deposition rate and the electrical resistivity of as-grown films as a function of the nitrogen-ion beam current of the gun II. Without supply of nitrogen through the gun II, the deposition rate of pure tungsten was 11.7 Å/min and the electrical resistivity was 210  $\mu\Omega$  cm. As the nitrogen-ion beam current increased to 120 mA, both the deposition rate and the electrical resistivity monotonically increased to 16.3 Å/min and to 1150  $\mu\Omega$  cm, respectively. These results indicate that the low-energy nitrogen ions were incorporated into the film. XPS analysis also revealed the presence of N in the film. A measured binding energy of a nitrogen 1s electron of 398 eV suggested that the nitrogen in the film exists as a  $WN$  compound.<sup>8</sup> N/W ratios of the films deposited under the nitrogen-ion beam currents of 40 and 120 mA were analyzed to be 0.27 and 0.70, respectively. Nitrogen concentration in the deposited film is almost proportional to the nitrogen-ion dose irradiated. From XRD analysis of all the grown films, no peak except for GaAs (200) and (400) planes was found, which indicates that the films deposited are amorphous. We attribute this result to the very low substrate temperature that is maintained at nearly room temperature during IBAD.

The Schottky properties of the IBAD  $WN_x$  contacts of various compositions  $x$  were investigated for annealing temperatures between 700 and 900 °C.  $100 \times 100 \mu\text{m}^2$  pads of the  $WN_x$  films with thicknesses of 600–1000 Å were defined by etching with  $H_2O_2$  through patterned photoresists. Since some  $WN_x$  films with high nitrogen concentrations of

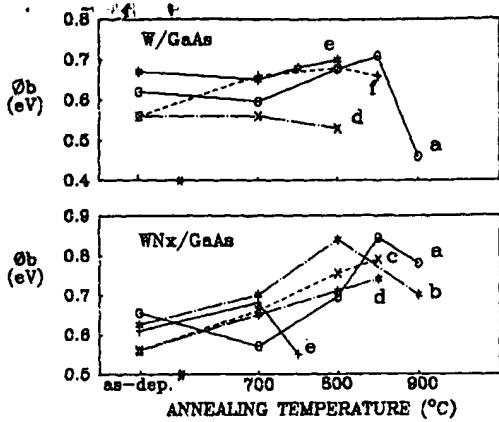


FIG. 4. Comparison of the annealing temperature dependence of Schottky barrier height for W and  $WN_x$ /GaAs diodes prepared by various methods and annealed in different conditions. (a) IBAD,  $SiO_2$ -capped, 30 min in  $N_2$ , this work; (b) rf sputtering, PSG-capped, 15 min in  $N_2$ , from Ref. 3; (c) dc magnetron sputtering,  $SiO_2$ -capped, 30 min in arsine, from Ref. 6; (d) dc magnetron sputtering,  $SiO_2$ -capped, 30 min in  $N_2$ , from Ref. 6; (e) dc magnetron sputtering, not specified from Ref. 7; (f) dc magnetron sputtering, capless, 30 min in arsine, from Ref. 6.

$x = 0.70$  showed considerable defects such as edge cracks and peeling off during cleaning procedure, we excluded these samples in the diode fabrication. Both sides of specimens were capped with 2000 Å thick  $SiO_2$  by chemical vapor deposition. Furnace annealing was subsequently carried out in the temperature range of 700–900 °C for 30 min in a nitrogen atmosphere. The  $SiO_2$  capping films were removed in a buffered HF solution, and then backside ohmic contacts were formed by deposition of AuGe and alloying at 470 °C. Current-voltage ( $I$ - $V$ ) measurement with a HP-4145B parameter analyzer was used to characterize the Schottky diodes. The Schottky barrier height  $\phi_b$  and the ideality factor  $n$  of the diode were determined from the  $I$ - $V$  plot in accordance with the ideal thermionic emission model.<sup>9</sup>

The Schottky properties of the contacts as-deposited and annealed at 850 °C are shown in Fig. 3 as a function of the nitrogen beam current during  $WN_x$  deposition. The ideality factor and  $\phi_b$  of the as-deposited W contacts were 1.16 and 0.62 eV, respectively. Annealing at 850 °C improved the Schottky characteristics significantly. The  $WN_x$  contacts grown under the nitrogen beam current of 40 mA equivalent to  $x = 0.27$  showed the highest  $\phi_b$  of 0.84 eV and the lowest ideality factor after annealing at 850 °C. It should also be mentioned that some of the  $WN_x$  contacts, grown under the nitrogen beam current of 80 mA which gives nearly  $x \approx 0.5$ , revealed  $\phi_b$  larger than 0.9 eV, although those revealed very poor uniformity even within a sample. The optimum nitrogen-to-tungsten ratio of 0.27 found in this study is close to 0.24 reported by Yu *et al.*,<sup>6</sup> who worked with dc magnetron sputtering, but is much higher than the values of less than 0.1 found by Uchitomi *et al.*,<sup>3</sup> Geissberger *et al.*,<sup>5</sup> and Josefowicz and co-workers.<sup>7</sup> This discrepancy is probably due to different deposition and annealing conditions.

In Fig. 4, we compared our preliminary results with previous data reported by several different methods. For W contacts, IBAD shows  $\phi_b$  of 0.71 eV, almost equivalent to the best result with dc magnetron sputtering.<sup>7</sup> Moreover, the diode obtained with IBAD is electrically stable up to 850 °C. From the data for  $WN_x$ /GaAs diodes, it is seen that the dc magnetron sputtering generally results in lower  $\phi_b$  than IBAD or rf sputtering. Also IBAD gives a high  $\phi_b$  of 0.84 eV that equals to the best result reported by Uchitomi *et al.*<sup>3</sup> with the rf sputtering. Besides the data given in Fig. 4, Yamagishi<sup>2</sup> also demonstrated good Schottky characteristics of rf sputtered  $WN_x$  contacts. Instead of  $\phi_b$ , he represented 0.95 eV of intrinsic barrier height  $\phi_b^0$  that equals to  $(\phi_b + \Delta\phi_b)$ , where  $\Delta\phi$  is the image force lowering of the barrier. Our calculation estimates  $\Delta\phi$  about 0.08 eV so that his results also appear similar to those by Uchitomi *et al.*<sup>3</sup> Even though there exist experimental differences between reports, the above comparison leads us to conclude that IBAD provides excellent W and  $WN_x$  films on GaAs whose Schottky properties are comparable to the best results obtained with the conventional reactive sputtering.

In summary, we demonstrated the formation of  $WN_x$  Schottky contacts on GaAs using a IBAD technique. Low energy nitrogen ions which were irradiated react with sputtered W evaporants, forming an amorphous  $WN_x$  film. By controlling the nitrogen dose, the composition and electrical resistivity of the  $WN_x$  film could be controlled. The  $WN_x$  films grown on GaAs by IBAD are promising for refractory gate materials in the self-alignment GaAs MESFET technology. The Schottky properties of  $WN_x$ /GaAs diodes investigated in the composition range from  $x = 0$ –0.47 were thermally stable up to 850 °C. The highest  $\phi_b$  of 0.84 eV uniformly obtained in this study was found in  $WN_{0.27}$ /GaAs diodes after annealing at 850 °C, although some of the  $WN_x$ /diodes ( $x$  about 0.5) showed  $\phi_b$  even larger than 0.9 eV. These preliminary results are comparable to the best results presented with reactive sputtering, and therefore, with designing more refined IBAD conditions, better Schottky characteristics are expected.

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